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CARBON NANOBIMORPH ACTUATOR AND SENSOR

5   CROSS-REFERENCE TO RELATED APPLICATION

This application is based on U.S. Application No. 60/262,690, filed January 19, 2001, the disclosure of which is incorporated by reference.

10   STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

The U.S. Government has certain rights in this invention pursuant to grant No. NAS 7-1407, awarded by the National Aeronautics and Space Administration, Office of Space Science.

15   FIELD OF THE INVENTION

The present invention is directed to a nanomechanical device, and more particularly to a nanomechanical device comprising self-assembled nanobimorphs for use as actuators, 20   oscillators and sensors.

BACKGROUND OF THE INVENTION

This invention relates in general to nanomechanical devices comprising motion controllable self-assembled 25   nanobimorphs, and in particular to self-assembled carbon nanobimorphs used as mechanical elements such as actuators and oscillators, or force detectors with single molecule sensitivity comprising a self-assembled carbon nanobimorph comprising at least two nanofeatures such as nanotubes arranged separately on 30   a pair of electrodes for applying a potential across the bimorph for either measuring the characteristic motion of, or creating a characteristic motion in the nanobimorph.

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Nanoscale structures are becoming increasingly important because they provide the basis for devices with dramatically reduced power and mass *and* enhanced capabilities. Practical nanotechnology-based applications will require nanoscale sensors and actuators for characterization and manipulation on the molecular scale. In addition, nanoscale elements that move will be essential for interfacing between the macro and nano-worlds: for fabrication of nanoscale structures, for characterization of those structures, and for coupling real-world inputs and outputs to molecular-scale electronics.

Nanoscale mechanical structures would also enable the fabrication of high-quality-factor (Q) mechanical resonators with high mechanical responsivity. Such devices can form very low-loss, low-phase-noise oscillators for filters, local oscillators, and other signal processing applications. High-Q resonators are critical components in communications and radar systems, as well as in MEMS-based sensors such as a micro-gyroscope. The combination of high-Q with small force constants enabled by nanoscale resonators would also produce oscillators with exceptional force sensitivity. This sensitivity is important for a variety of force-detection-based sensors and may ultimately allow single molecule spectroscopy by NMR and optical techniques.

Nanoscale actuators and oscillators are also key components of mechanical signal processing systems. For example, actuators can be used to produce switches and mechanical transistors, while oscillator arrays containing elements with controllably varying resonant frequencies form the basis for high-speed Fourier analysis, similar to the frequency-dependent signal processing done in biological hearing systems. Mechanical signal processing

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is of great interest because small-scale, high-Q mechanical elements may theoretically enable processing at GHz rates with orders-of-magnitude lower power dissipation than conventional CMOS processors.

The emerging carbon nanotube technology offers exciting possibilities for producing useful nanoscale actuators and mechanical oscillators. Probing and manipulating on the molecular scale will require tools of a similar size. Carbon nanotubes provide a unique bridge between the macroscopic and nano-worlds because they have nanometer cross-sectional dimensions combined with tube lengths that can reach fractions of a millimeter. Nanotubes are well suited for use as robust, high-Q oscillators, because they possess near perfect molecular bonding coupled with extremely high tensile strength, and they exhibit elastic deformation even at high bending angles.

Despite the potential for these nanomechanical devices, the practical application of nanotube-based actuators and oscillators has been limited by the development of growth and processing methods for control of nanotube placement and orientation. These techniques are critical for a wide variety of other nanotube applications including nanotube electronic systems.

One novel approach to making nanometer-scale structures utilizes self-assembly of atoms and molecules to build up functional structures. In self-assembled processing, atom positions are determined by fundamental physical constraints such as bond lengths and angles, as well as atom-to-atom interactions with other atoms in the vicinity of the site being occupied. Essentially, self-assembly uses the principles of synthetic chemistry and biology to Agrow@ complex structures from a set of

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basic feedstocks.   Utilizing such techniques molecular motors have been synthetically produced containing fewer than 80 atoms.

5   Chemical vapor deposition (CVD) appears to be the most suitable method for nanotube production for sensor and electronic applications. CVD uses a carbon-containing gas such as methane, which is decomposed at a hot substrate surface (typically 600-900C) coated with a thin catalyst film such as Ni or Co.

10   However, most studies to date have produced disordered nanotube films.

A notable exception is the work of Prof. Xu who has developed a new technique for producing geometrically regular

15   nanotube arrays with excellent uniformity in nanopore templates. *Xu et al. Appl. Phys. Lett., 75, 367 (1999)*, incorporated herein by reference.   Post-patterning of these ordered arrays could be used to selectively remove tubes in certain areas or produce regions with different length tubes. A variety of other studies

20   have shown that dense, but locally disordered arrays of normally-oriented nanotubes can be selectively grown on pre-patterned catalyst layers.   However, none of the current techniques have been able to grow vertical individual nanotubes or small groups of nanotubes with integrated electrodes, as would be necessary

25   to form nanotube oscillators or actuators.

In addition, there has been little progress in the control of nanotube orientation in the plane parallel to the substrate surface. Many of the basic electrical measurements of nanotubes

30   have been done using electrodes placed on randomly scattered tubes after growth, or by physically manipulating tubes into place with an atomic force microscope (AFM). Dai and co-workers have been able to demonstrate random in-plane growth between

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closely spaced catalyst pads, including growth over trenches, as well as a related technique to produce nanotubes suspended between Si posts. *Dai. Et al., Science, **283**, 512 (1999)*, incorporated herein by reference. In these cases individual nanotubes sometimes contact adjacent electrodes by chance, and excess tubes can be removed with an AFM tip. This type of procedure can be effective for simple electrical measurements, but considerable improvements will be required for production of more complex nanotube circuits. Smalley's group has demonstrated a wet chemistry-based method of control over nanotube placement using solution deposition on chemically functionalized substrates, although questions remain about nanotube length control and contact resistance. *Smalley et al., Nature, **391**, 59 (1998)*, incorporated herein by reference. However, none of the current techniques have been able to grow vertical individual nanotubes or small groups of nanotubes with integrated electrodes, as would be necessary to form nanotube oscillators or actuators.

In addition to the problems associated with controlled growth and orientation of nanotubes, nanotube actuators and oscillators also require a transduction mechanism to convert input signals to physical motion and to provide corresponding output signals.

One possible mechanism is suggested by a recent demonstration that nanotube mats can serve as very high efficiency electromechanical actuators in an electrolyte solution, with the possibility of even better results for well-ordered single wall tubes. *Baughman et al., Science, **284** 1340 (1999)*, incorporated herein by reference. Other potential

actuation mechanisms to be investigated include light-induced
nanotube motion, which has been observed, and magnetomotive

5   actuation. However, these techniques have only been demonstrated
for large disordered arrays of nanotubes, no technique has been
developed for the controlled motion of individual nanotube
bimorphs

10   Accordingly, a need exists to develop nanoscale mechanical
devices, such as, actuators and oscillators to enable
applications ranging from molecular-scale characterization and
manipulation, to ultra-low-loss mechanical filters and local
oscillators for communications and radar, to rad-hard low-power

15   mechanical signal processors.

SUMMARY OF THE INVENTION

The present invention is directed to a nanomechanical
device and system utilizing nanobimorphs comprising at least two

20   adjacent nanofeatures, such as nanotubes, in a touching relation
at one end, and means for inducing a difference in charge
density between the tubes (e.g. by biasing one tube positive
with respect to the other with sufficient tube-to-tube contact
resistance) such that lateral movement is induced in the end of

25   the bimorph, forming a nanoscale actuator, as well as a force
sensor when operated in an inverse mode. The invention is also
directed to growth techniques capable of producing a novel
nanotube bimorph structure with integrated electrodes.

30   In one embodiment this invention utilizes a nanobimorph
with an integrated electrode substrate that functions as an
oscillator or actuator. This invention is also directed to a
device which utilizes a nanobimorph with an integrated electrode

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substrate that functions as a molecular sensor. This invention is also directed to novel systems and methods for utilizing devices comprising at least one nanobimorph with an integrated electrode substrate.

In another embodiment, the invention is directed to a nanobimorph actuator comprising a nanobimorph with an integrated electrode substrate. The nanoscale actuators of the present invention are designed to provide the capability of controllable motion on near-atomic scales. In such an embodiment, the transduction mechanism is symmetric – length changes in the nanotubes will induce charge transfer and hence voltages, providing a readout mechanism for the actuators.

In another alternative embodiment, the induced voltage is produced by optical irradiation.

In still another embodiment, the invention is directed to nanobimorph oscillators or resonators. The nanobimorph oscillators may be utilized as high-Q mechanical resonators for filters, signal processing, and sensors. In such an embodiment, excitation and readout of a nanobimorph oscillator may be made using the actuation methods previously discussed in the nanobimorph actuator section: piezoelectric, light, or electrostatic.

In yet another embodiment, the invention is directed to mechanical signal processing systems utilizing the nanobimorph actuators and oscillators of the current invention. For example, in one embodiment, actuators can be used to produce switches and mechanical transistors, while in another embodiment oscillator arrays containing elements with controllably varying resonant frequencies form the basis for high-speed Fourier signal processing.

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In still yet another embodiment the nanotubes comprising the nanobimorph self-assemble into the nanobimorph having a specified diameter and height suitable for use in the devices of the current invention.

In still yet another embodiment, the substrate is made of a semiconductor such as, for example, oxidized silicon or aluminum oxide, coated with a metal catalyst film such as, for example, Ni or Co. In this embodiment, the silicon can be further doped to adjust the electronic properties of the substrate surface.

In still yet another embodiment, the nanotubes comprising the nanobimorph are self-assembled from an inert material such as, for example, carbon utilizing a carbon feedstock gas such as, for example, ethylene.

In still yet another embodiment, the invention is directed to a system for the detection of substances comprising multiple detectors as described above, such that parallel processing of molecules can be carried out.

In still yet another embodiment, the invention is directed to growth and processing techniques to control nanobimorph location and orientation; and methods for positioning nanotubes during growth, including nanoscale patterning of catalyst dots to seed the growth of vertical nanotubes on integrated electrodes.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

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FIG. 1 is a schematic view of an embodiment of a nanobimorph according to the invention.

FIG. 2 is a schematic view of an embodiment of a nanobimorph in operation as an actuator or oscillator according to the invention.

FIG. 3 is a schematic view of an embodiment of a nanobimorph in operation as a sensor according to the invention.

FIG. 4a is a schematic view of an embodiment of a process for forming a nanobimorph according to the invention.

FIG. 4b is a schematic view of an embodiment of a process for forming a nanobimorph according to the invention.

FIG. 4c is a schematic view of an embodiment of a process for forming a nanobimorph according to the invention.

FIG. 4d is a schematic view of an embodiment of a process for forming a nanobimorph according to the invention.

FIG. 5 is an SEM image of an embodiment of spatially ordered nanotube growth according to the invention.

FIG. 6a is an SEM image of an embodiment of nanotubes grown at a temperature of 411 °C according to the invention.

FIG. 6b is an SEM image of an embodiment of nanotubes grown at a temperature of 456 °C according to the invention.

FIG. 6c is an SEM image of an embodiment of nanotubes grown at a temperature of 500 °C according to the invention.

FIG. 6d is an SEM image of an embodiment of nanotubes grown at a temperature of 550 °C according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed to a device and system utilizing nanobimorphs comprising at least two nanofeatures,

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such as nanotubes, and means for inducing a difference in charge density between tubes (e.g. by biasing one tube positive with respect to the other with sufficient tube-to-tube contact resistance) such that lateral movement is induced in the end of the bimorph, forming a nanoscale actuator/oscillator, as well as a force sensor when operated in an inverse mode. These devices will be collectively referred to as nanomechanical devices herein.

As shown in FIG. 1, the nanomechanical device **10** according to the invention generally comprises a substrate **12**, having first **14** and second **16** electrodes, and nanobimorph **18**, comprising first **20** and second **22** self-assembled nanotubes arranged on nucleation points **24** on the first **14** and second **16** electrodes of the substrate **12** such that the nanotubes are spaced apart from each other at an end proximal to the substrate and attractively attached at an end distal from the substrate.

The nanomechanical device shown schematically in FIG. 1 has two basic modes of operation: an actuator/oscillator mode, shown in FIG. 2 and a sensor mode shown in FIG. 3. As shown in FIG. 2, in the actuator mode, the nanobimorph **10** acts as a transducer, converting an input signal **26** into a mechanical action **28**. In this embodiment, a voltage is applied between the nanotubes with sufficient tube-to-tube contact resistance to create a charge difference and thereby produce a deflection of the bimorph structure, corresponding to an expansion for the negatively-biased tubes **20** and a contraction for the positively-biased tubes **22**. As shown in FIG. 3, when the nanobimorph **10** is operated in the inverse mode, subtle changes in the position of the nanotubes, i.e., a deflection **28** cause by an impinging

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molecule **29** will induce a voltage across the two nanotubes producing an output signal **30** which can be measured by an external monitoring device **32** in signal communication with the electrodes **14** and **16** of the bimorph **10**. In addition, the nanobimorph can act as a molecular detector when operating as an oscillator by measuring shifts in the mechanical resonance frequency induced by attached molecules. Such a detector can be made to be chemically specific by functionalizing the nanotubes to attach to specific molecules.

The charge induced motion and motion induced charge discussed above have previously been observed in random arrays of carbon bimorph mats and in graphite sheets, see, e.g., R. Baughman, cited above, incorporated herein by reference. Although not to be bound by theory, it is believed that the nanotube length change is caused by "quantum chemical effects", that is, changes in orbital occupation and band structure result in changes in the C-C bond distances and thus the length of the nanotube. It should also be noted that the charge-induced transduction mechanism is symmetric, i.e., length changes in the nanotubes will induce charge transfers and hence voltages, providing a readout mechanism and/or positional sensor for both actuators and oscillators. Although the Baughman experiments were done in electrolytic solutions, it should be understood that no electrolytic solution is required so long as direct electrical contact is made with each nanotube. Alternatively, although the charge-induced actuation mechanisms shown in FIGs. 1 to 3 are only depicted in non-liquid environments, which are useful for high-Q oscillator applications, it should be understood that the nanotube electromechanical transduction

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effect can be compatible with operation in liquids, such as for use in biological actuators.

Any nanofeature suitable for use as an actuator/oscillator bimorph may be utilized in the current invention. In a preferred embodiment, as shown in FIGs. 1 to 3 and discussed above, a carbon nanotube bimorph is utilized. Carbon nanotubes possess a combination of properties that make them well suited for use as nano-actuators. For example, nanotubes combine a nanometer scale diameter with a large aspect ratio, good electrical conductivity, and elastic bending. Single-wall nanotubes also have a Young's modulus of approximately 1 TPa, which corresponds to strength/weight ratio approaching 200 times that of steel. The combination of this high Young's modulus and the ability to withstand large strains (~5%) suggests that SWNTs should also have very high breaking strengths. These properties indicate that nanotubes can interact at the nanoscale level, but are also long enough and strong enough to couple efficiently to the macro-world. In addition, the observed electromechanical response of these initial nanotube actuators is quite large. For example, it has been observed that nanotube sheets exhibit significantly larger stresses than human muscle and higher strains than the best ferroelectric materials. In fact, carbon nanotubes have a volumetric work capacity that is more than 29 times higher than any other known material.

Even though such electrode or direct control deflection could be utilized for low-frequency motion, higher frequency electrostatic drive for nanoscale structures may be limited by parasitic capacitances. However, it is well known that C nanotubes show a direct coupling between optical irradiation and their mechanical properties. Accordingly, in an alternative

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embodiment an optical based actuation technique could is utilized for coherent stimulation of nanotube arrays for

5   mechanical signal processing applications.

Although the above discussion has been directed to the actual nanotube bimorph actuator according to the present invention, it should be understood that the invention is also directed to suitable nanomechanical devices comprising the

10   nanobimorph actuators shown schematically in the above figures. For example, nanoscale actuators provide the capability of controllable motion on near-atomic scales, and as such, these devices provide the basis for characterization, manipulation, and fabrication at sizes less than 100 nm. Some exemplary

15   applications include: characterization of individual molecules by chemical AFM with functionalized nanotube probes, and even actual assembly of custom molecules and nanoscale structures. In short, the nanobimorph actuators according to the present

20   invention provide small-scale elements that move in response to an input signal which in turn provide the means for interfacing the macroscopic and molecular worlds.

In other embodiments, nano-actuators of the current invention could be utilized as macro-inputs to control and

25   measure nanoscale structures, and could serve as I/O couplers to molecular computers. For example, one implementation of a Quantum Cellular Automata (QCA) computer relies on the bistable positioning of electron pairs. In such an embodiment, the position state of a local pair could be switched or read out by

30   mechanical flipping of a molecular dipole by a nano-actuator. In another alternative embodiment, nanometer-scale actuators could be utilized to provide the means for motion of cell-sized robots. Finally, in another alternative embodiment, nano-

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actuators could be used to fabricate components for low-power mechanical signal processing, such as nano-relay switches and

5   mechanical transistors.

Although the above discussion has focussed on nano-actuator embodiments of the invention, the mechanical resonators can also be utilized as high quality oscillators. The natural rigidity and structural perfection of the nanotubes, discussed

10   above, indicates that the nanobimorph system according to the present invention should function as a high-Q mechanical resonator for many devices, such as, for example, filters, signal processors, and sensors. Since nanotubes naturally occur with nanoscale diameters, they are well suited for fabrication

15   of oscillators with large aspect ratios and associated high responsivity. The lowest order resonant frequency for a nanotube cantilever is given by:

$$\nu_j = \frac{(1.875)^2}{8\pi} \frac{1}{L^2} \sqrt{D^2 + D_i^2} \sqrt{\frac{E_b}{\rho}} \qquad (1)$$

where L is the length, D and D_i are the outer and inner diameters, E_b is the elastic modulus, and   is the density (1.33

25   g/cm^3). For a cantilever with D = 10 nm, D_i = 8 nm, and 100 nm in length, this formula predicts a resonant frequency of approximately 4 GHz. This frequency would more than double for a nanotube oscillator fixed on both ends. Note that since

30   nanotube lengths can be varied over the range of approximately 10 nm to 100μm, we should be able to control resonant frequencies over 8 orders of magnitude.

Such nano-structures also exhibit extremely high quality factors, for example, Q values of mechanical oscillators range

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from 10^3 to 10^9, with values of 10^3 to 10^5 for nanoscale structures in vacuum. These Qs are much larger than typical quality factors for electronic resonant circuits, accordingly, mechanical resonators such as quartz crystal oscillators are used in communications systems. Because Q varies as 1/D, where D is the internal dissipation, high Q values correspond to low-loss system components. High quality factors also translate to exceptional oscillator stability and low phase noise. Such low-phase-noise local oscillators (LO) are critically important for narrow-bandwidth communications and sensitive doppler radars. For example, the LO phase noise sets the minimum detectable velocity for Doppler radar. In another embodiment, such high-Q oscillators could also be utilized as narrow-band, low-loss filters, and improve the stability and sensitivity of MEMS-based sensors such as a micro-gyroscope.

Moreover, by moving to nanoscale mechanical structures, it is possible to combine high Qs with high frequency operation and small force constants (high responsivity). Calculations indicate that Si mechanical oscillators with realistically achievable dimensions (0.1 x 0.01 x 0.01) have resonant frequencies of a few GHz. High resonant frequencies are important for producing mechanical signal processing components compatible with today's characteristic circuit clock rates. Resonators with nanoscale dimensions can achieve GHz resonant frequencies in structures with reasonably large aspect ratios, which translates directly to small force constants. The combination of high-Q with small force constants enabled by nanoscale resonators results in oscillators with exceptional force sensitivity. Accordingly, in one embodiment the nano-resonator may be utilized in the inverse mode for a variety of force-detection-based sensors and if

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properly functionalized allows for the possibility of single molecule spectroscopy by NMR and optical techniques.

5   Although optical read-out techniques are discussed above, excitation and readout of a nanobimorph oscillator could be done using the actuation methods previously discussed in relation to the nanobimorph actuator embodiment: charge-induced transduction, light, or electrostatic. In addition, for a

10   nanobimorph oscillator attached to electrodes at both ends, it is possible to use a "magnetomotive" technique, in which the Lorenz-force interaction between an alternating current flowing in the oscillator beam and a magnetic field applied normal to the beam generates a force perpendicular to the beam and applied

15   field. The transverse motion of the beam in turn produces an induced voltage along the length of the beam, which can be detected by a network analyzer.

The signal monitor system for any of the above detection

20   schemes can comprise any suitable circuit or device capable of measuring the signal change from the detector and transmitting that information to the user, such as, for example, a printed circuit board having a pre-amplifier, an AD converter and driver circuit, and a programmable chip for instrumentation specific

25   software; or a multichip module comprising those elements.

In another embodiment, the nanoscale actuators and oscillators discussed above may also be utilized in mechanical signal processing systems. Mechanical signal processing is of great interest because small-scale, high-Q mechanical elements

30   theoretically enable processing at GHz rates with up to *six orders of magnitude* lower power dissipation than conventional CMOS processors of comparable complexity. In addition, such devices would be radiation tolerant, an important property for

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space-based applications.   For example, in one embodiment, a nanobimorph actuator according to the invention can be used to produce switches and mechanical transistors.   In another embodiment, a nanobimorph oscillator array according to the invention containing elements with controllably varying resonant frequencies could be utilized for high-speed Fourier signal processing, mimicking the mechanical processing that occurs in mammalian ears.

Returning to the structure of the underlying nanobimorph system **10**, shown in FIGs. 1 to 3, it should be understood that the substrate **12** can be made of any material which can withstand the temperatures required for growth of the nanotubes **20** and **22** and which can be modified to provide suitable ordered pairs of nucleation points **24** for growing the nanotubes **20** and **22** of the nanomechanical device **10**, such as, for example, metallized Si oxide wafers, anodized alumina, glass, or even polymeric plastics.   In turn, any suitable electrode and catalyzing metal can be used for the electrodes **14** and **16** and to activate the nucleation points **24** on the surface of the substrate **12**, such as, for example, nickel or cobalt.   Alternatively, the catalyzing metal could be an alloy of two or more metals such as a Co/Ni or Ti/Ni alloys.   The metal catalysts could also be produced by pyrolysis of inorganic or organic metal-containing compounds, such as, for example, Ferric Nitrate or Cobalt Chloride.   Accordingly, in the limit of sub-50 nm catalyst dots **24**, it is possible to nucleate growth of a single nanotube **20** or **22** at each catalyst location.   Integrated electrodes **14** and **16** can be produced by combining the catalyst dots with non-catalytic electrodes.   This ability to precisely locate

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individual nanotubes and make electrical contact to each tube provides the basis for fabrication of vertically aligned bimorph and oscillator structures.   Such a method may utilize an electron-beam lithography system.

One possible process for forming the nanomechanical device **40** of the present invention comprising nanotube bimorphs **42** and **44** utilizing a chemical vapor deposition (CVD) technique is shown schematically in FIGs. 4a to 4d.   In a first step, as shown in FIG. 4a, a substrate **46**, such as, for example, silicon is coated with a high purity metal film, such as, for example, Ti.   The metal is then patterned in a multistep process to produce electrodes **48** and **50** in ordered pairs on the substrate **46**.   Next, a small amount of catalytic material **52**, such as, for example, Co or Ni is deposited by electrochemical means or by physical vapor deposition on electron-beam defined catalyst patterns on the electrodes to serve as a catalyst for carbon nanotube **42** and **44** growth, as shown in FIG. 4b.   As shown in FIG. 4c, the electrodes and catalyst are partially exposed by dissolving away the electron beam resist in an appropriate solvent such as acetone.   Finally, as shown in FIG. 4d, the nanotubes **42** and **44** are self-assembled by pyrolysis of a suitable feedstock, such as, for example, ethylene gas diluted in nitrogen and/or ammonia and/or hydrogen at about 650 C.   The electrodes **48** and **50** and the catalyzed dots **52** serve as a template such that the nanotubes **42** and **44** self-assemble in a bimorph pair corresponding to the dots **52** in the anodized metal substrate **46**.   After the adjacent nanotubes **42** and **44** have grown sufficiently to allow interaction, the van der Waals attraction between the adjacent tubes is sufficient to ensure that the

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tubes will become attached along their sidewalls at their distal ends, as shown in FIGs. 1 to 3.

5   A potential embodiment of the invention includes a modification of the nanotube growth process to increase the contact resistance between the two tubes in the bimorph by including an additional gas or gases such as fluorine, for example.   Post growth treatments using appropriate gases or

10   liquids can also serve the same purpose.

Although one method for the self-assembly of carbon nanotubes is described above, it should be understood that in order to incorporate the carbon nanotube bimorph actuators and oscillators on CMOS electronics it is necessary to provide

15   carbon nanotube growth at temperatures compatible with processed CMOS circuits, i.e., below about 500 °C. Although any suitable method of low temperature growth may be utilized, some exemplary methods include: 1) Murikami et al. (*Appl. Phys. Lett.* **76** *(13)*,

20   *1776 (2000)*) method for growing aligned carbon nanotube arrays for field emission at <600 °C using bias-enhanced microwave plasma CVD on patterned, nickel-based catalyst at 1-3 Torr; 2) Li et al. (*Appl. Phys. Lett.*, **79** *(11)*, *1670 (2001)*) method of

25   unaligned nanotube growth on glass at 570 °C using CVD at 100 Torr; 3) low temperature processes for growing carbon nanotubes on silicon (*Choi et al., J. Vac. Sci. Technol. A,* **18** *(4)*, *1864 (2000)*): using 70 nm nickel films as a catalyst deposited on silicon substrates coated with TiN as an adhesion enhancement

30   layer) and silicon dioxide (*Lee et al.,Chem. Phys. Lett.* **327**, *277 (2000)*) between 500-550 °C; 4) Zhang and Iijima (*Appl. Phys. Lett.,* **75** *(20)*, *3087 (1999)*) method for growing single-walled carbon nanotubes at 400 C using laser ablation technique with

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powdered catalyst containing Ni-Co; and 5) Chen et al. (*J. Cryst. Growth, 193, 342 (1998)*) method of growing graphitic nanofibers on nickel substrates at 350-400 °C. All of which are incorporated herein by reference.

FIG. 5 shows a scanning electron microscope (SEM) image of the results of patterned growth using one preferred low-temperature growth method comprising: annealing the substrate (30 minutes at 653 °C) prior to growth, followed by plasma assisted growth under a gas pressure 5 Torr (90% ethylene, 10% hydrogen) with a dc bias of about 100V. In the example shown in FIG. 5, an Fe catalyst was utilized. The catalyst was sputtered on the silicon substrate at a thickness of between about 0.3 to 1.0 nm. Using a similar such technique a series of high resolution tunneling electron microscope (HRTEM) images of nanotubes grown at temperatures from as low as 411 to 550 °C using a NiTi catalyst are shown in FIGs 6a to 6b.

While the self-assembled bimorphs contemplated in the embodiments discussed so far have been constructed of carbon nanotube bimorphs made from pyrolizing an ethylene feedstock over a substrate having an ordered array of nucleation points, the bimorphs can be of any shape and made by any process and from any material suitable for making self-assembled nanobimorphs, such as, for example, spheres or pyramids made of other atomic materials or even biomolecules, such as, for example, proteins. In another embodiment, the bimorphs are further functionalized for a variety of applications, such as, for example, being made hydrophilic or hydrophobic, being charged either negatively or positively, or being derivatized with specific chemical groups, etc. In addition, although only

an untreated carbon nanotube nanomechanical device have been shown thus far, *in situ* sidewall treatments could further increase the tube-to-tube contact resistance, to increase the charge differential induced by a given applied voltage.

In addition, although in the embodiments shown thus far the nanomechanical device **10** according to the present invention comprises a pair of vertically aligned nanotubes **20** and **22** grown on e-beam written catalyst dots **24** with integrated electrodes **14** and **16**, as shown in FIG. 1. Any spacing or pattern of catalyst dots **24** and electrodes **20** and **22** may be utilized such that the van der Waals attraction between adjacent tubes is sufficient to ensure that the tubes become attached along their sidewalls at their distal ends, as shown in FIG. 1. In addition, while the embodiments shown thus far described a pair of nanotubes (one on each electrode), the present invention could also function as an effective actuator or oscillator using multiple tubes grown on each electrode, and could provide greater actuation forces, for example in that configuration. Alternatively, actuators and force sensors with more than two electrodes are also possible and would enable motion and detection in more than a single plane of operation.

Although as discussed above, an oscillator geometry comprising a nanobimorph with electrical contacts to both nanotubes is preferred, any suspended nanobimorph structures with a bias source capable of controllably applying a bias between the nanotubes or alternatively for measuring the bias across the nanotubes in a detector mode may be utilized. For example, systematic variations of critical geometric factors may include the nanotube lengths and electrode attachment.   As

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another example, it is also possible to produce a nanobimorph in the plane of the substrate, suspended over a trench.

Finally, although the above discussion has focussed on the construction and structure of the nanobimorphs, it should be understood that a nanomechanical device according to the invention may also include a body, a self-contained power supply, and any additional machinery or circuitry necessary for the device's operation. For example, the body of the nanomechanical device itself can be made of any material suitable for micromachining utilizing standard lithographic or MEMS techniques to enclose the bimorph, such as, for example, aluminum oxide or silicon. In a preferred embodiment, the body further comprises a cap layer which can be of any design such that the cap layer protects the bimorph from unwanted contact with the external environment. Such a cap layer could be made of any suitable material, such as, for example, aluminum oxide or silicon. Such a cap layer could be formed by any conventional MEMS process, such as growth or deposition over a sacrificial layer (not shown) deposited to encapsulate the self-assembled nanobimorph wherein the sacrificial layer can subsequently be removed to expose the self-assembled nanobimorph itself. Alternatively, these support structures could be formed in a single deposition step with the self-assembled nanobimorph. In a more preferred embodiment, one of the substrate, the cap layer, or walls of the nanomechanical device is transparent such that an optical source can be used to interrogate or activate the nanobimorph.

In another alternative embodiment the nanomechanical device comprises an array of multiple nanobimorphs aligned on a single substrate such that multiple or parallel processing can

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be carried out at one time.   In this embodiment, the bimorphs can be integrated into a single circuit or detector.   It should be understood that while arrays of bimorphs are discussed above, any suitable alternative geometry of bimorphs may be utilized. Such an embodiment could be used to develop a mobile bimorph detector device on a chip for mobile detection and analysis of samples.   In such an embodiment a portable power source (not shown) would also be integrated into the device.

Although specific embodiments are disclosed herein, it is expected that persons skilled in the art can and will design alternative nanomechanical devices and methods to produce the nanomechanical devices that are within the scope of the following claims either literally or under the Doctrine of Equivalents.

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